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Advanced Research Projects Agency (ARPA)
Contracts Management Office (CMO)
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Attention: Mr. Douglas M. Pollock

Subject: Contract No. MDA972-93-C-0057; GTEL Project No. 852
Quarterly Technical Report (SLIN 0002AB)

Dear Mr. Pollock:

GTE Laboratories Incorporated hereby submits the subject report covering the period February 23, 1995 through May 23, 1995, in accordance with the terms of the Contract.

If you should have any questions or require any additional information or further clarification, please contact me at (617)466-2954.

Sincerely,

Deidre B. Ryan
Contracts Manager

Enclosure

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The CRO unit was completed and shipped to Stanford for incorporation in the network testbed. Evaluation of polarization stability of the CRO has revealed a significant difference between the GTE Laboratories environment and Stanford's laboratory. Progress was made in development of the digital optical switch; and another RIE mask with finer segmentation in each curved region has been designed. The first "proof of principle" of operation of 2 x 2-switches has been demonstrated using previously fabricated X-switches. Finally, in mid-April, 75% of the wafers ordered from EPI products arrived.

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METHODS AND COMPONENTS FOR OPTICAL CONTENTION RESOLUTION IN HIGH SPEED NETWORKS

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1. CONSORTIUM EXECUTIVE SUMMARY

The CRO unit was completed and shipped to Stanford for incorporation in the network testbed. The shipment (thermally controlled air-ride van was used) was completed successfully with no mechanical damage to the unit. GTE's personnel participated in testing and re-tuning of the unit upon arrival in Stanford. Two of the optical components exhibited increased insertion losses and were subsequently repaired at GTE. This restored the original performance.

Evaluation of polarization stability of the CRO has also revealed a significant difference between the GTE Laboratories environment and Stanford's laboratory. The polarization which was stable for hours at GTE, varies much faster at Stanford. The origin of this instability is not obvious at the present time however the cooling system, building vibrations, air movement could all contribute to this. GTE is working closely with Stanford to resolve this issue.

Progress was made at GTE Laboratories in development of the digital optical switch. The device was re-designed for single mode operation and this new waveguide structure appears to provide the desired single mode switching operation. This was observed directly by examining the output beam profiles and resulted in good extinction ratio of Y-switches of 15-25 dB. (See attached figures). Moreover the wide range of switching current values brings this design closer to practicality.

The throughput losses in the fabricated batch is still high due to a design software feature which requires segmentation of curved sections. To reduce this loss, another RIE mask with finer segmentation in each curved region has been designed This improved mask was received from the vendor and devices were fabricated. The measurements show a significant reduction in radiation losses by a factor of two (~5.6 dB/curve) in the curved regions. Further improvements in this figure are being implemented at the present time.

The first "proof of principle" of operation of 2x2 X-switches has been demonstrated using previously fabricated X-switches made with the initial non-packageable switch mask set. These devices were made using the previous mask set and therefore were not truly single mode. This resulted in switch operation with 10 dB extinction ratio but only at a few isolated current values. We expect that the switches fabricated using the new mask set will demonstrate much better performance in terms of extinction ratios.

After a delay of about three months, 75% of the wafers ordered from EPI products arrived in mid April. The rest will follow. This will permit us continued fabrication and development of the optical switch. Considering the progress made in recent months (i.e. successful design and fabrication of single mode devices, implementation of curved waveguides, implementation of new measurement set up, preliminary results showing the "proof of principle" of optical X-switches, availability of new wafers) we expect to demonstrate 2x2 optical digital switches within the next few months.

During the seventh quarter of the CORD project (2/15/95 through 5/14/95), Stanford University has continued experimental investigation of the CORD testbed. The majority of our effort has been the characterization and integration of the Contention Resolution Optics (CRO) preprototype, which we received from GTE Laboratories on March 6, 1995. Of primary concern, is the instability of the optical signal polarization as it progresses through the CRO. The CRO contains LiNbO3 optical switches which have switching characteristics dependent on the polarization of the optical signal. Therefore, any drift in polarization has drastic effects on the extinction ratio, or cross-talk, of the switch.

We have narrowed the source of the polarization instability to four sources: the 100 m single mode fiber delay line; the 50 m polarization maintaining fiber (PMF) delay line; the polarization monitors; and the semiconductor optical amplifiers (SOAs). We have found that the 100 m single mode fiber delay line is considerably more stable when coiled at a larger radius. Therefore, GTE Laboratories will ship us a replacement spool for the delay line to be coiled around. We have performed numerous experiments with the PMF delay lines but have not conclusively determined the source of instability. We strongly suspect that the connectors are not correctly aligned to the core of the PMF, possibly caused during the shipment of the CRO. If that is the case, we will have the alignment and hence the instability in the PMF delay lines, corrected shortly. Because the polarization monitors are fusion spliced between several other devices, we have not performed isolated measurements on them, but have strong evidence that they are causing larger losses than expected and some instability as well. We have decided that the penalties caused by the polarization monitors outweigh their benefits and plan to bypass them in the CRO. To compensate for the polarization shift through the SOAs, we have installed additional polarization controllers. This arrangement provides sufficiently stable polarization through the SOAs for many hours of operation without the need for re-adjustment.

A part from the polarization instability, the CRO integration has been fairly successful. Initial eye diagram measurements indicate that the power margin will be sufficient for the testbed system. We tested our switch driving circuitry with the LiNbO3 optical switches and were able to achieve switching speeds of less than 6 nsec, fast enough for efficient switching of the 250 nsec slots used in the CORD testbed. In addition, we completed the printed circuit board layout for the 8-to-64 bit payload data demultiplexer and have added more features to the control channel transmitter and receiver modules.

During the past quarter University of Massachusetts group has achieved the following significant results:

A. Completion of evaluation of the multi-buffer design for the two stage CRO architecture, including control strategies and delay line sizing

B. Completion of the software modules necessary to emulate reconfigurable optical devices and timed operations of optical devices (e.g., switching time)

A. Evaluation and Strategies for Multi-buffer CRO Design: In two previous reports the University of Massachusetts team presented preliminary results on the multi-buffer delay line CRO design. In particular we presented two strategies that can be used to control the CRO built for CORD: one can be used when both delay lines are one slot long, the other to improve the CRO performance when the first delay line is one slot long and the second delay line is m2 slot long, with m2>1. In addition, we reported preliminary results on using the CRO in a 2x2 switch node, showing the benefits of the multi-buffer approach using a specific control strategy which makes use of the local information consisting in all the packet currently stored in the CRO. In the past quarter University of Massachussetts has completed a comprehensive analysis of the multi-buffer approach in a two stage CRO device to be used in either a 2x1 (Y configuration) or a 2x2 (X configuration). We have extended the results presented in previous reports by:

1. elaborating a design for the control strategy which does not require the information on the type and position of all the packets stored in the CRO,

2. proposing three different control strategies for the Y configuration,

3. proposing three different control strategies for the X configuration,

4. finding and proving optimality for a strategy under certain traffic conditions,

5. presenting the asymptotic results for the proposed strategies,

6. presenting performance results for the proposed strategies under non-bursty as well as bursty traffic conditions,

7. developing models to evaluate the performance and asymptotic behavior of the above strategies under non-bursty traffic conditions,

8. executing simulation to evaluate performance of the proposed strategies under bursty traffic conditions.

The Contention Resolution Optic (CRO) device currently being tested at Stanford University consists of three 2x2 photonic space switches and two delay lines, each with a length equal to the space traveled by the light signal in one time slot. The storage capacity of the CRO is hence equal to two optical packets. It is well known from queuing theory that the performance of a buffer is proportional to its storage capacity. In principle, the storage capacity of the CRO device (i.e., the number of stages, each comprising one delay and one switch) can be increased indefinitely to match the required performance.

However, a CRO with a large number of stages is not practical as each additional stage in the CRO requires an additional 2x2 switch. This leads to two fundamental problems:

1. The cost for the CRO increases due to the additional switches and the additional optical amplifiers required.

2. The additional insertion loss determined by the added switches might not be acceptable by the system, either because the optical power budget is not sufficient, or the maximum level of noise already reached in the system does not allow to use additional optical amplifiers.

These fundamental problems have been one of the major concerns in the CRO design and involved a relatively large part of the University of Massachussetts team effort. The research direction that was taken lead to the principle of increasing the storage capacity of the CRO without increasing the number of stages by lengthening the DLs. The additional fiber required to lengthen the DLs is neither a problem in cost, nor a concern in terms of potential optical losses. The dimension introduced by the multi-buffer DL design offers a new space to explore and requires the solution of two problems: determining the optimal length for each DL and determining the strategy to control the multi-buffer DL CRO. The solution for either problem is not independent from the other and the optimal configuration is not trivial to identify. In this quarterly report issued by UNiversity of Massachussetts we address the two design problems mentioned above for a 2x1 CRO such as the one used in the CORD project and for a 2x2 CRO used in a switch node with two input fibers and two output fibers.

B. Developing Modules for Simulation: In the past quarter we continued the development of the integrated optical network simulator. During this period, we concentrated on two specific types of optical devices, wavelength sensitive devices and receiver devices. In the past we described representation details for transmitters, switches and receivers. In the last quarter a higher level of detail was introduced in optical receiver modeling. Also, a support mechanism for wavelength sensitive optical devices was implemented. We also developed simulation of simple network architectures for debugging and correctness evaluation of the package. Simplicity and flexibility of the representation of optical devices are issues of concern in the optical network simulator, and have been carefully evaluated. The simulator must provide easy procedures for the specification of optical device and the definition of the interconnections necessary to describe the network under study. In addition, a newly added function enables delayed device state update to model latency, such as the switching time in photonic switches.

The Integrated Optical Simulator project is entering its final stage which will be completed in the next three months. We have developed representation for the existing optical devices and their interconnection to form an optical network. The resulting flexibility of the package allows us to simulate any existing optical network topology together with the access protocols specifically designed for the network. Therefore, in the final stage of the simulator design we will continue the debugging process by developing simulation of various optical networks, combining the description of the basic characteristics of the optical physical layer with the description of the access protocol specified in Estelle. In addition, we will critically examine the source code for redundancies and comments to enhance quality and readability of software.

During the next quarter we will also analyze the extension of the 2x1 two stage CRO architecture to the more general Nx1, n>2 stage CRO architecture to evaluate the scalability properties of the CORD approach to 1) a large number of wavelengths (N) and 2) a large number of stages (n) when very low probability of packet loss is a mandatory feature in the optical network under design.

The following sections contain the technical report of GTE Laboratories only. Stanford University and University of Massachusetts will submit their reports separately.

2. TECHNICAL SUMMARY

2.1 CRO

The CRO unit was completed and shipped to Stanford for incorporation in the network testbed. The shipment (thermally controlled air-ride van was used) was completed successfully with no mechanical damage to the unit. Optical testing revealed, however degradation of two optical interfaces in side the CRO box. Subsequent evaluation of the degradation indicated that it was likely a result of chemical interaction between the index matching gel used in assembly of some of the optical components and plastisizers in the packaging material. The observed result of this was formation of "crystallites" in the gel causing power loss in the lightwave signal. The two degraded devices (header detector and polarization monitor) were re-opened, the "crystallized" gel removed and fresh gel re-inserted. This restored the original performance of these devices.

Evaluation of polarization stability of the CRO has also revealed a significant difference between the GTE Laboratories environment and Stanford's laboratory. The polarization which was stable for hours at GTE, varies much faster at Stanford. The origin of this instability is not obvious at the present time however the cooling system, building vibrations, air movement could all contribute to this. GTE is working closely with Stanford to resolve this issue.

2.2 DIGITAL OPTICAL SWITCH

Packageable passive single-mode optical waveguides (modulators, X and Y-switches) have been successfully fabricated using a new waveguide design. Experimental results show that the new design (ridge height ~1 μm, ridge width ~3.6 μm) completely eliminates the higher-order modes in the waveguides. This was observed directly by examining the output beam profiles and resulted in good extinction ratio of Y-switches. The extinction ratio measured was in the range of 15-25 dB. Figure 1 shows power output of a Y-switch vs. applied current.

In the current injection mode the digital optical switch operates over a wide range of injected current values. This is in contrast to interferometric switches (Mach-Zender or directional couplers) , where the response is periodic with the applied control signal strength resulting in a very narrow range of signal values for device operation in a high extinction ratio regime. For example, LiNbO3 switches used in the CRO (Mach-Zender) require application of bias and switching voltages to within around 1% to maintain the rated extinction ratio of 20 dB. More over the digital optical switches do not require bias currents simplifying the operation and making these devices much more practical. Figure 2 shows the range of switching currents used in testing the fabricated devices. A range of about 10 mA about the nominal 30 mA, good extinction ratio can be expected.

Measurements of throughput losses reveal that radiation losses in the curved sections of the packageable X and Y-switch structures were high (~12 dB/curve). This appears to be caused by design-software feature in the curved region. The design software requires segmentation of curved sections. These segments are then connected by the mask generating program into a single curve. However, because of the way this software performs this operation, jogs are formed in the fabricated waveguides causing optical power loss in the propagating signal. To reduce this loss, another RIE mask utilizing 70 segments in each curved region was designed. This finer segmentation reduces the discontinuity in the waveguides and thus the losses. This improved mask was received from the vendor and devices were fabricated. The measurements show a significant reduction in radiation losses by a factor of two (~5.6 dB/curve) in the curved regions. A third RIE mask consisting of 600 segments has been designed and is presently being used in fabrication to further reduce the radiation loss. The rest of the packageable switch mask plates, including the electrode metallization and the scribe alley masks, have been designed and received from the vendor. Complete current-injectable packageable switches are in the fabrication stage at this point.

The first "proof of principle" of operation of 2x2 X-switches has been demonstrated using previously fabricated X-switches made with the initial non-packageable switch mask set. Since that mask design was not optimized for single mode operation, the waveguides supported higher-order modes. This made the output characteristics of both the active and the passive arms oscillatory. Thus, acceptable extinction ratios (~10 dB) could only be obtained at those values of injection currents where the higher-order modes has a minimum, which was different for each electrode and switch. The extinction ratio also changed with the alignment of the fibers, because the mixture of the higher-order modes changes with fiber alignment. Thus, acceptable performance was not attainable. Since the use of the newly designed packageable mask set eliminates the higher-order modes from the waveguides completely, it is expected that the switches fabricated using this mask set will demonstrate much better performance in terms of extinction ratios.

A new characterization set up with adjustable fiber alignment at either of the two input ports (for X-switches only) at an angle of ~ 23° from the perpendicular (separated from each other by ~46°) and at either of the two output ports at similar angles has been designed and built. This system is capable of simultaneously aligning fibers to packageable X-switches, two at the input and two at the output end for switch performance measurements. It has been successfully tested on fabricated passive X-switch structures.

After a delay of about three months, 75% of the wafers ordered from EPI products arrived in mid April. The rest will follow. This will permit us continued fabrication and development of the optical switch. Considering the progress made in recent months (i.e. successful design and fabrication of single mode devices, implementation of curved waveguides, implementation of new measurement set up, preliminary results showing the "proof of principle" of optical X-switches, availability of new wafers) we expect to demonstrate 2x2 digital optical switches within the next few months.

3. MILESTONES

1. Fabrication of a digital optical switch with extinction ratio >20 dB.

Feasibility of producing high extinction ratio digital optical switches has been demonstrated for Y-structure devices. X-switches are in progress and are expected to produce similar performance.

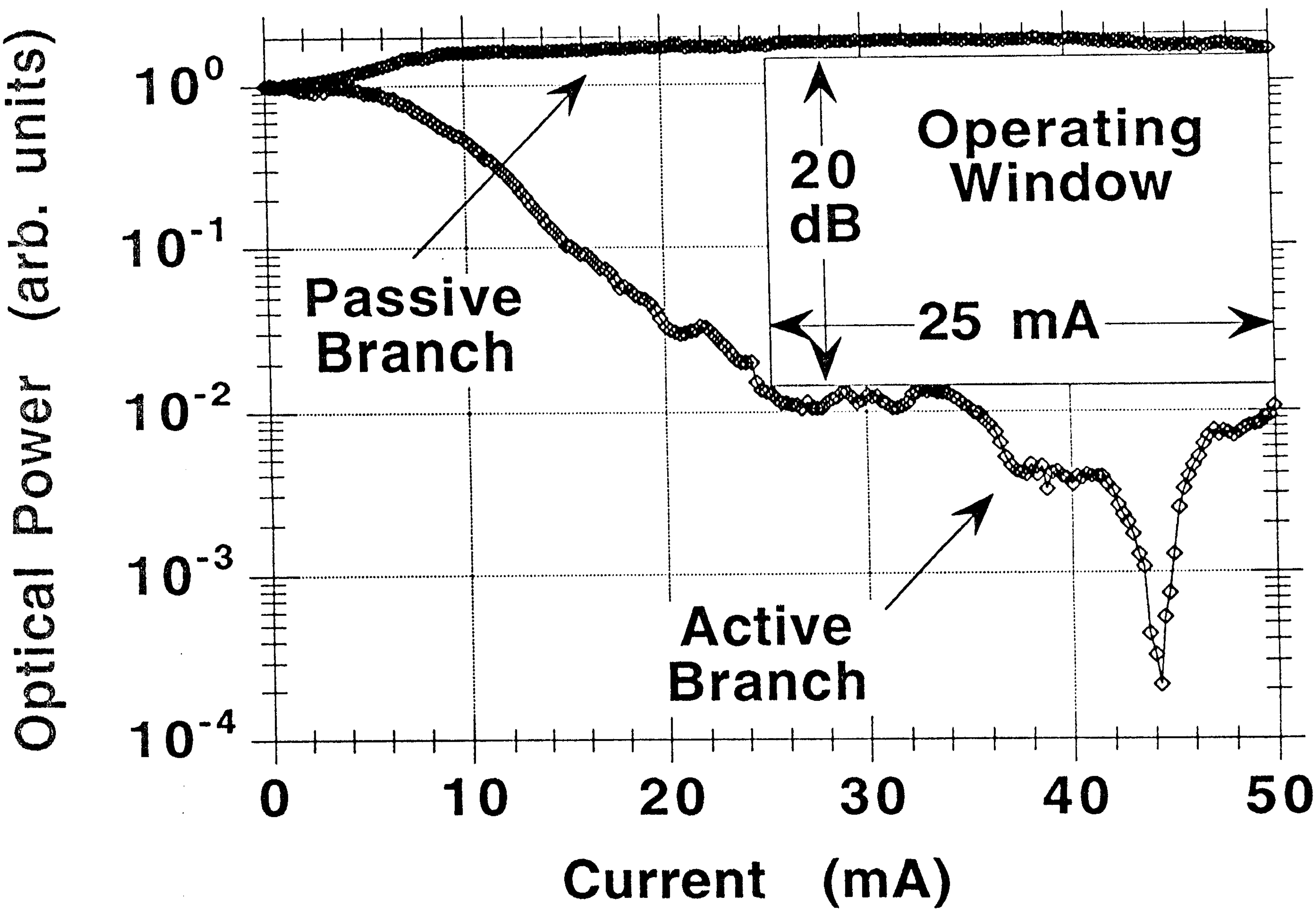
2. Optimization of switch design for high speed operation.

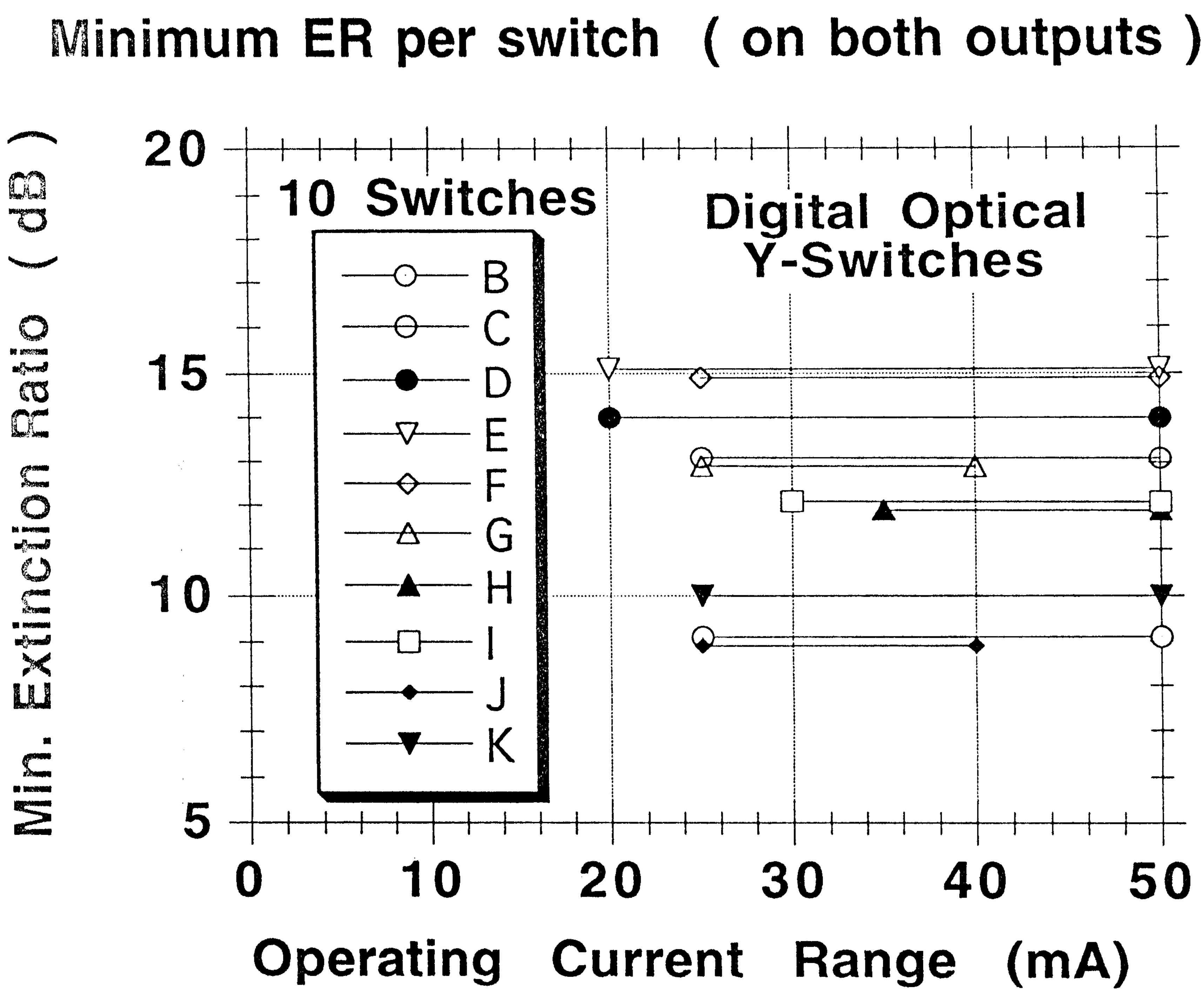
Delayed till full completion of milestone 1.

3. Testing of CRO pre-prototype.

Testing of the CRO assembly has been completed at GTE prior to shipment to Stanford University.

Integrated Digital Optical Y-Switch Package




Minimum ER per switch (on both outputs)
Min. Extinction Ratio (dB)
20
15
10
5
10 Switches
B
C
D
E
F
G
H
I
J
K
Digital Optical
Y-Switches
0
10
20
30
40
50
Operating Current Range (mA)